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IGNITION AND WIND EFFECTS ON THE TRANSITION TO FLAME SPREAD IN A MICROGRAVITY ENVIRONMENT

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Introduction

Although the fundamental processes involved in ignition [1]–[4] and flame spread [5], [6] have been extensively studied, they are generally studied separately without combining ignition and flame spread through the transition process. Moreover, the majority of the flame spread studies assume steady state flame spread. To study the transient aspects of ignition and the transition to flame spread, a time-dependent numerical model has been developed in which a thin strip is ignited along its width with either a pilot wire, radiative source, or both. For this configuration, the model is two-dimensional. Ignition is initiated away from either end of the sample, and two different flame fronts spread in opposite directions; one flows with and the other against a prescribed external flow. Usually, the flame spread is initiated by ignition at one end of the sample with or against a slow external flow [7], yielding one flame front. The present configuration is more realistic than the one flame front case because there is interaction between the two flames during the ignition and transition stages. A complete description of the mathematical model is given in Ref. [8].

Wind Effects

In normal gravity, concurrent flame spread rates are typically much faster than opposed flow spread rates. For an opposed flow flame, the unburned thin fuel is heated primarily by gas phase conduction. For a concurrent flame, however, the spread is enhanced by the increased heat transfer due to the forced convection of, and radiation from, the hot flame products over the unburned fuel. For both types of flames, buoyancy provides fresh oxidizer and removes combustion products. In microgravity, however, buoyancy is negligible, and it has been observed experimentally that opposed flow flames are stronger than concurrent flow flames.

To demonstrate the effect of microgravity on flame spread, both experiments and numerical simulations of flame spread along a strip were carried out with and without a slow external wind. Fig. 1 compares the numerical and experimental flame spread profiles for both a 2 cm/s windblown and a quiescent simulation. The ambient oxygen concentration in both cases is 30%. For the numerical simulation, the flame spread rate for the quiescent case is about 1.6 cm/s (both directions) while the upstream flame spread rate for the windblown case is about 1.5 cm/s. The upstream flame in this case is about 60% stronger than the quiescent flame, as measured by the peak gas phase reaction rate. The downstream flame, however, is weaker than the quiescent flame by a factor of about 4. The maximum temperature for the upstream flame was about 1820 K, whereas the quiescent flame was about 1760 K. The downstream flame had a maximum temperature of about 1400 K after 3 s, but notice in Fig. 1 that the downstream flame is gradually weakening and slowing down. Eventually the flame dies out.

The experimental flame spread profiles for this case show that the external wind does not significantly

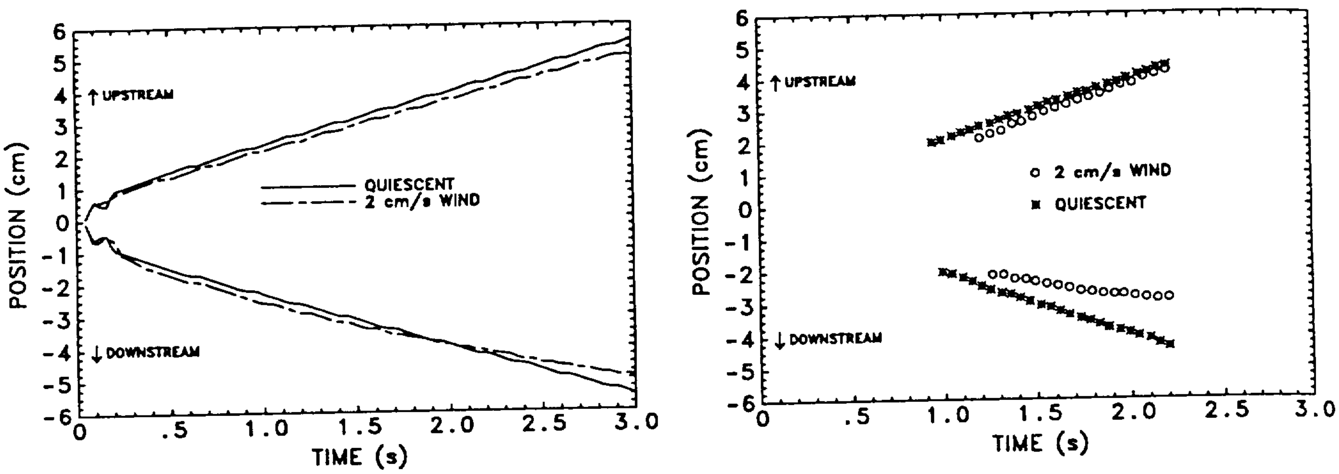

Figure 1: Numerical (left) and experimental (right) flame spread profiles for external winds of 0 and 2 cm/s in 30% oxygen.

change the spread rate of the upstream flame, while it considerably weakens the downstream flame. It has been observed in the drop tower experiment that the upstream flame in the presence of the 2 cm/s wind is slightly faster than the quiescent counterpart, but not significantly. The downstream flame tip is weakened considerably relative to the upstream and quiescent cases. These flame tips were primarily sooty, unlike the upstream leading edge which was invariably blue. It is not clear in the short test time if this flame tip would have continued to propagate. The numerical downstream flame ceases to spread after about 4 s.

A closer examination of the reaction zones for the numerical upstream and downstream flames is shown in Fig. 2. Included in the figure are contours of the oxygen and fuel mass fractions. The dependence of the upstream flame spread rate on flow velocity has been attributed to oxidizer transport effects [9], or radiative loss effects [6]. The experiments and numerical simulations both show a strengthening of the upstream flame due to increased oxidizer transport in the presence of a slow external wind. It has been observed in both the experiments and in the simulations that the stand-off distance and overall width of the upstream flame is reduced due to the external wind. This would help explain the increased reaction rate and heating of the sample surface.

The downstream flame is initially weakened by the presence of the upstream flame, but as the two flames separate it becomes clear that the downstream flame is inherently weaker than the upstream flame. Even though the convective heat transfer to the unburned fuel is greater for the downstream flame compared to the upstream or quiescent flames, the downstream flame is weaker than both, and in this case, appears to be dying out as was seen in the experiment. Because the difference between the flame spread rate and the wind speed is small, there is a reduced convective contribution of fresh oxidizer and removal of combustion products in the downstream flame relative to the quiescent counterpart. The gradient of the oxygen mass fraction in the vicinity of the peak reaction zone points out the effect of the wind.

Ignition Effects

In general, the mode of ignition has little, if any, effect on the final steady state flame spread assuming, of course, that the transition to flame spread occurs. However, the development of the flame from ignition to steady state greatly depends on the mode of ignition. For example, the transition from ignition to flame spread for a radiative source is characterized by an initial rapid flame spread, then a gradual decrease in velocity until the final steady state is reached. If the radiative flux distribution is wide, there will be more preheating of the sample prior to ignition and hence more rapid flame spread for the transition period

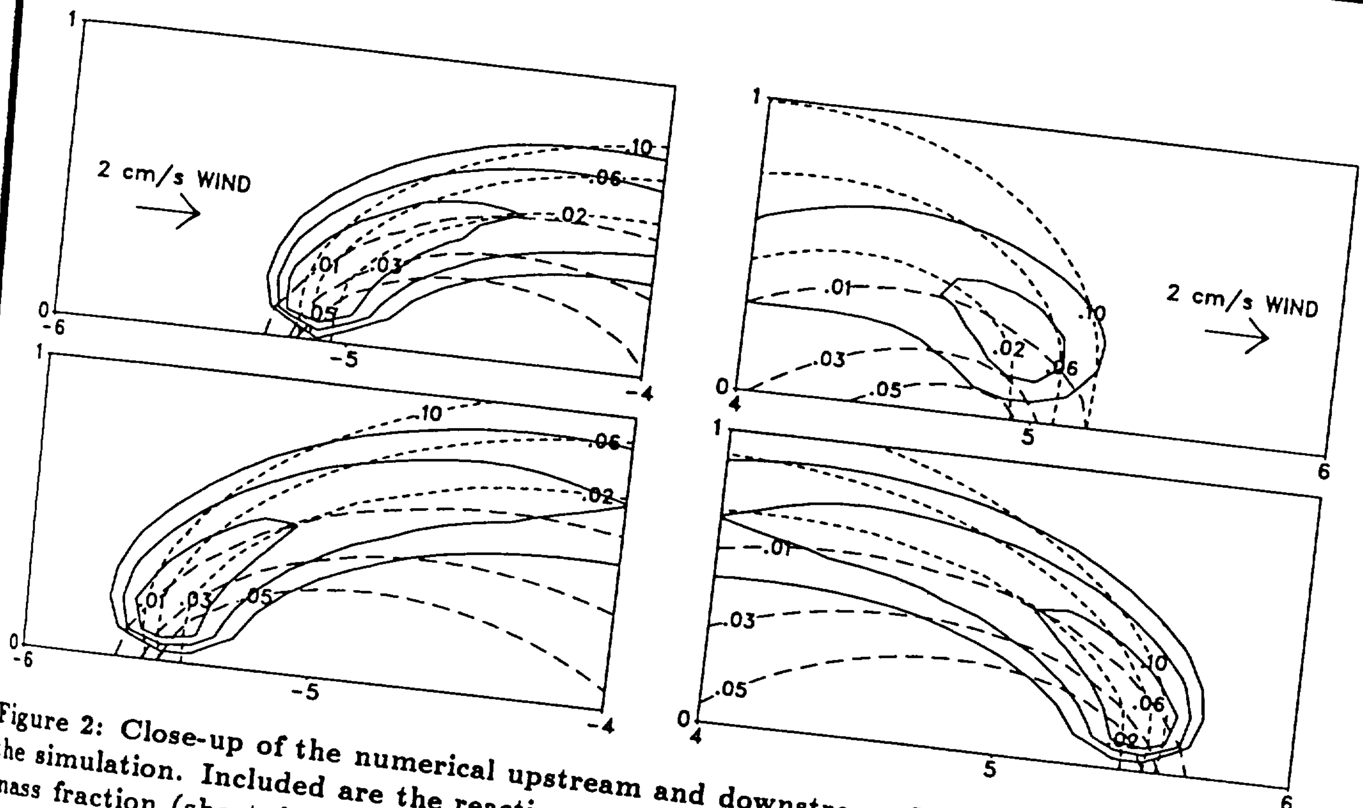

Figure 2: Close-up of the numerical upstream and downstream flames 3 s after the start of the simulation. Included are the reaction rate contours (solid lines), along with the oxygen mass fraction (short dashes) and fuel gas mass fraction (long dashes). The horizontal axis represents the distance (cm) from the ignition point.

following ignition. Piloted ignition, however, is characterized by a short transition to steady state flame spread because there is very little preheating of the sample ahead of the flame front.

A major difficulty in performing physical experiments of ignition and flame spread is the initial heating of the sample. A numerical study was carried out to assess some of the trends affecting the ignition process, both piloted and unpiloted. Five unpiloted runs were conducted in which the width of the Gaussian radiative source was altered, but the integrated heat flux was held constant. The results are summarized in Fig. 3. Ignition is triggered most rapidly by a sharp radiative flux distribution, but for the less sharp case, the preheating of the sample away from the ignition region leads to a flame which initially travels at a higher rate of speed and ultimately travels farther in the same amount of time, although in all cases the flames ultimately achieve the same steady state spread rate.

Future Work

To investigate a wider variety of flame spread scenarios, a three-dimensional version of the above numerical model has been written and some preliminary simulations have been made. Even though the mathematical model is relatively simple, the 3D calculations are very challenging because of the fine resolution required to capture the large temperature gradients in the vicinity of the reaction zone. The results of these calculations will also be presented along with the results of the 2D simulations discussed above.

Acknowledgments

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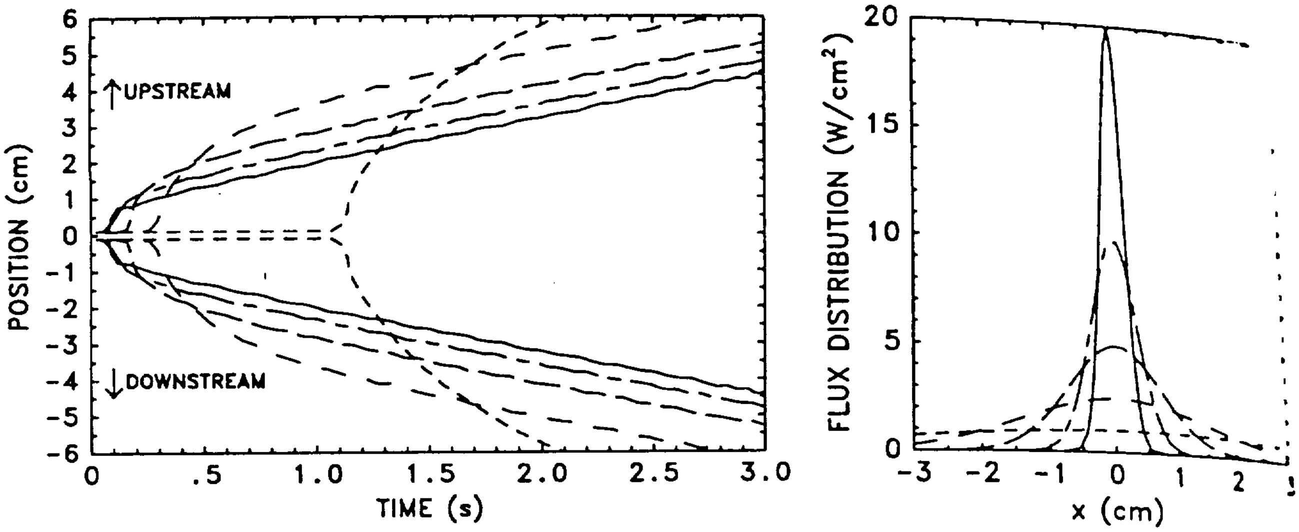

Figure 3: Flame spread profiles for various radiative source distributions, all of which have the same integrated heat flux. The oxygen concentration is 30%; there is no external wind.

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